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The cyclic Rørdal Member – a new lithostratigraphic unit of chronostratigraphic and palaeoclimatic importance in the upper Maastrichtian of Denmark

FINN SURLYK, LARS STEMMERIK, MORTEN AHLBORN, RIKKE HARLOU, BODIL W. LAURIDSEN, SUSANNE L. RASMUSSEN, NIELS SCHOVSBO, EMMA SHELDON & NICOLAS THIBAUT



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The Maastrichtian chalk of the Danish Basin has been referred to the Tor Formation of the North Sea, but this may not be tenable because this formation in its type area shows a much higher degree of redeposition than the Maastrichtian chalk of the Danish Basin. The onshore succession has not been lithostratigraphically subdivided due to its rather monotonous nature and the widely scattered outcrops. An exception is the uppermost Maastrichtian exposed at Stevns Klint which is been referred to the Sigerslev Member, comprising rather benthos-poor, deep-water pure chalk, and the overlying mound-bedded, bryozoan-rich chalk which is placed in the Højerup Member. In addition, a thin marly chalk bed, the Kjolby Gaard Marl Member, containing Tethyan planktonic foraminifers is known from localities in northern Jylland and from water wells around Køge, eastern Sjælland. The new Rørdal Member is a cyclic chalk-marl unit, about 10 m thick, sandwiched between pure white chalks. It is well exposed in the large Rørdal quarry in Aalborg, and is recognised in boreholes south of Aalborg and in the Stevns-1 and Karlslunde-1 boreholes south of Copenhagen. Coccolith and brachiopod data show that it belongs to the UC20b-c^{BP} nannofossil zone of the North Sea scheme for the Upper Cretaceous Boreal province, and the *semiglobularis-humboldtii* brachiopod zone, both indicating the lower upper Maastrichtian. Isotope data show that it represents a distinct early late Maastrichtian cooling event. The member thus has a basinwide distribution and is an important isochronous marker because it represents a significant change in sea-water temperature and not a progradational event.

Keywords: Lithostratigraphy, cyclicity, chalk, marl, Rørdal Member, Maastrichtian, Denmark.

Finn Surlyk [finns@geo.ku.dk], Lars Stemmerik [ls@geo.ku.dk], Morten Ahlborn [ma@geo.ku.dk], Rikke Harlou [rh@geo.ku.dk], Bodil W. Lauridsen [bodill@geo.ku.dk], Nicolas Thibault [int@geo.ku.dk]. Department of Geography and Geology, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. Susanne L. Rasmussen [slr@geus.dk], Niels Schovsbo [nsc@geus.dk], Emma Sheldon [es@geus.dk]. The Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.

Corresponding author (finns@geo.ku.dk)

All outcropping Upper Cretaceous chalk of the Danish Basin belongs to the Maastrichtian Stage (Surlyk 1984). Lower Maastrichtian chalk is well exposed at Møns Klint, upper Maastrichtian chalk is exposed in quarries around Aalborg in northern Jylland, and uppermost Maastrichtian chalk is exposed along the length of the 14 km long coastal cliff, Stevns Klint, and in small outcrops in northern Jylland (Fig. 1).

The Maastrichtian chalk of the Danish Basin is referred to the rather unfortunately named Chalk Group but has not been systematically lithostratigraphically classified and subdivided due to the monotonous li-

thology, scattered nature of the outcrops, and lack of long continuous outcrop sections. It has with some hesitation been referred to the Tor Formation of the North Sea (Surlyk *et al.* 2003, 2006) but ongoing work on the fully cored scientific Stevns-1 and -2 boreholes (Stemmerik *et al.* 2006; Schovsbo *et al.* 2008; Thibault *et al.* 2009; Thibault 2010) will hopefully allow a detailed lithostratigraphic subdivision of the upper Campanian – Maastrichtian chalk of the Danish basin. The top Maastrichtian exposed at Stevns Klint has recently been referred to the Sigerslev Member, comprising rather benthos-poor, deep-water pure chalk,

and to the overlying mound-bedded, bryozoan-rich chalk of the Højerup Member (Surlyk *et al.* 2006). A thin but distinctive marl bed, the Kjølby Gaard Marl Member of Troelsen (1955), containing Tethyan planktonic foraminifers is known from the uppermost Maastrichtian at several localities in northern Jylland and from water wells and other wells around Køge and Copenhagen, eastern Sjælland.

The outcropping Maastrichtian chalk of Denmark was subdivided into a total of ten brachiopod zones by Surlyk (1970, 1972, 1984). This zonation has been extended to Hemmoor and Kronsmoor in northern Germany (Surlyk 1970, 1982), Norfolk in eastern England (Johansen & Surlyk 1990), and was correlated with the brachiopod zones of Steinich (1965) on the island of Rügen in north-eastern Germany. The Danish Maastrichtian is also referred to belemnite zones (Birkelund 1957; Christensen 1996, 1997; Schulz & Schmid 1983) but belemnites are only common in the lower Maastrichtian chalk of Hvide Klint and Møns Klint; they are very rare in the uppermost Maastrichtian of Stevns Klint, and virtually absent in the Maastrichtian of western Denmark. Recent work on coccoliths from the Stevns-1 and Rørdal-1 cores (Sheldon 2008; Thi-

bault *et al.* 2009) has allowed correlation with the Boreal coccolith zonation of the North Sea established by Burnett (1998) and Fritsen (1999). A $\delta^{13}\text{C}$ curve has been established for the Stevns-1 and Rørdal-1 cores and this makes it possible to undertake detailed chronostratigraphic correlations of the upper Campanian – Maastrichtian chalk of the Danish Basin (R. Harlou unpublished data; Schovsbo *et al.* 2008; Thibault *et al.* 2009). Stevns-1 provides an excellent $\delta^{13}\text{C}$ standard reference curve for this stratigraphic interval in the Boreal Realm.

The new Rørdal Member defined here represents a marked deviation from the otherwise rather monotonous Maastrichtian chalk in that it is markedly cyclic with alternating chalk and marl beds (Lauridsen & Surlyk 2008; Schovsbo *et al.* 2008). It is well exposed in the large Rørdal quarry in Aalborg and is identified in boreholes south of Aalborg and in the Stevns-1 and -2 and Karlslunde-1 boreholes south of Copenhagen (Fig. 1). The aim of the present study is to define the cyclic unit as a formal member, to demonstrate its chronostratigraphic significance, and to highlight its importance as a palaeoclimatic signal.

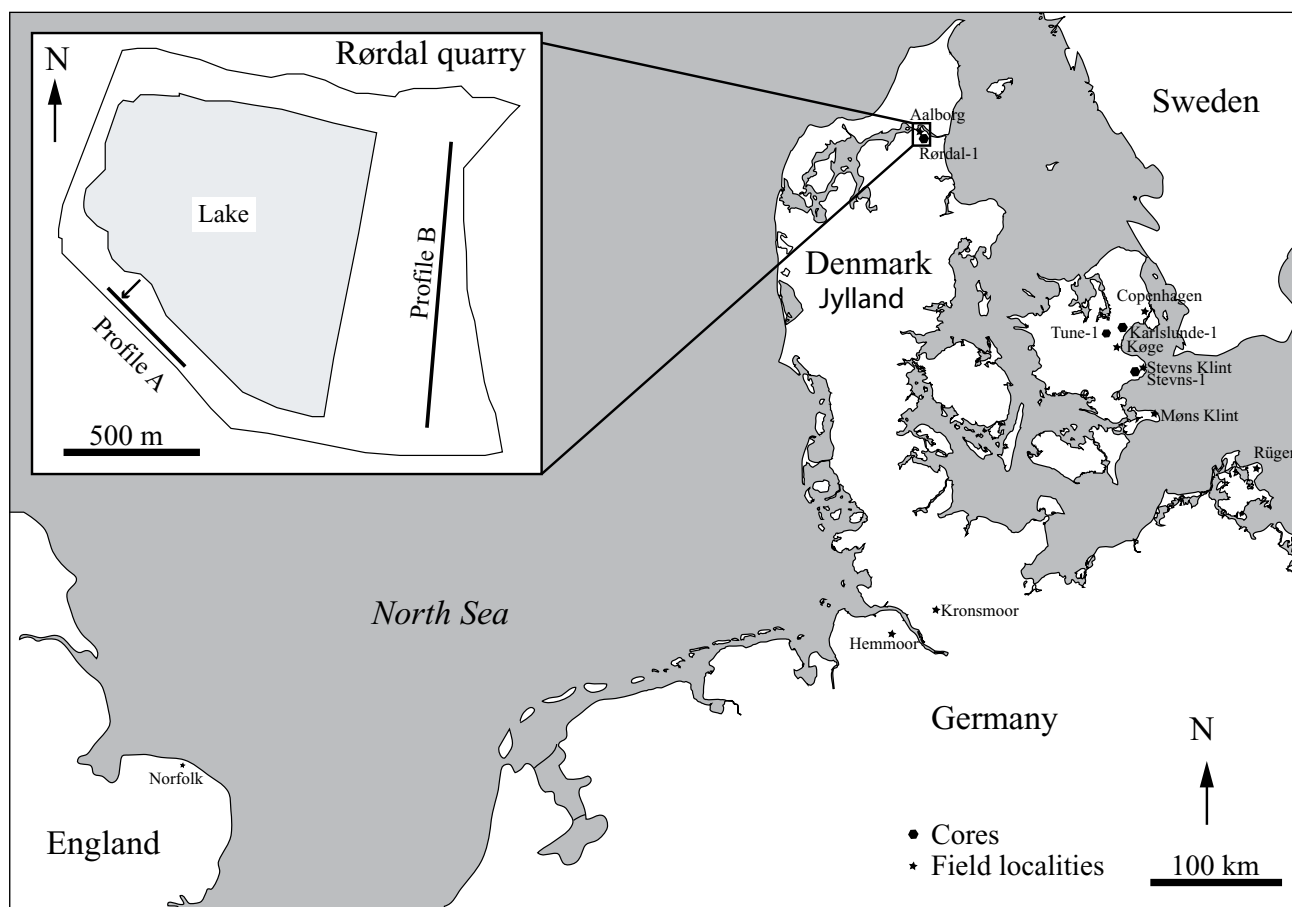


Fig. 1. Map showing position of localities mentioned in the text. Inset a map of the Rørdal quarry. Profiles A and B are illustrated in Figure 2. Arrow pointing at profile A indicates the position of the type section (Fig. 2A).

Lithostratigraphy

Rørdal Member

New member

Name

After the large Rørdal quarry situated in eastern Aalborg, northern Jylland (Fig. 1).

History

The member was first identified by Surlyk (1970) but at that time only the lowest thin marl bed was exposed. It was correlated with marl bands at Rügen and Hemmoor on the basis of brachiopod stratigraphy and was interpreted as a possible bentonite. A few years later the full cyclic succession became exposed (F. Surlyk and E. Stenestad, unpublished data, 1976) and was figured by Stenestad (2005, 2006). Recently it formed the basis for palaeoecological studies of the benthic invertebrates and trace fossil assemblages and their response to the cyclic changes in substrate lithology (Lauridsen & Surlyk 2008; Lauridsen *et al.* in press).

Type and reference locality

The uppermost part of the south-western wall of the Rørdal quarry is designated as the type section (Figs 1, 2A, B, 3). It is somewhat overgrown and weathered, but marks the final extent of the quarry and will not be further excavated. Excellent exposures are at present (2009) seen in the eastern quarry wall which, however, is subject to ongoing quarrying (Fig. 2C). The Karlslunde-1 and Stevns-1 boreholes (Stemmerik *et al.* 2006; Bonnesen *et al.* 2009) serve as reference localities (Figs 1, 4).

Thickness

The member is about 9 m thick in the type section as estimated from the thickness of the interval, comprising eight distinctive peaks on the gamma-ray profile (Fig. 3). A slightly different thickness was measured in the field due to difficulties in adequate estimations in the trench of the sloping quarry wall exposing slightly dipping beds (Fig. 3). The marl beds are 30–60 cm thick and the intervening chalk beds are 60–120 cm thick in the type section. In the gamma ray log the marl beds are measured as 30–65 cm thick and the intervening chalk beds as 50–110 cm thick (Fig. 3). The carbonate content is 71–82% in the marl beds and 82–92% in the chalk beds (Fig. 3).

In the Stevns-1 reference section, the correlative suc-

cession shows up to ten gamma ray peaks. However, only the lowermost five of these are associated with marly beds and are referred to the Rørdal Member. The member is approximately 9 m thick, from 105.05–96.20 m, and is characterised by only five marl beds, 5–10 cm thick, separated by 20–220 cm thick beds of

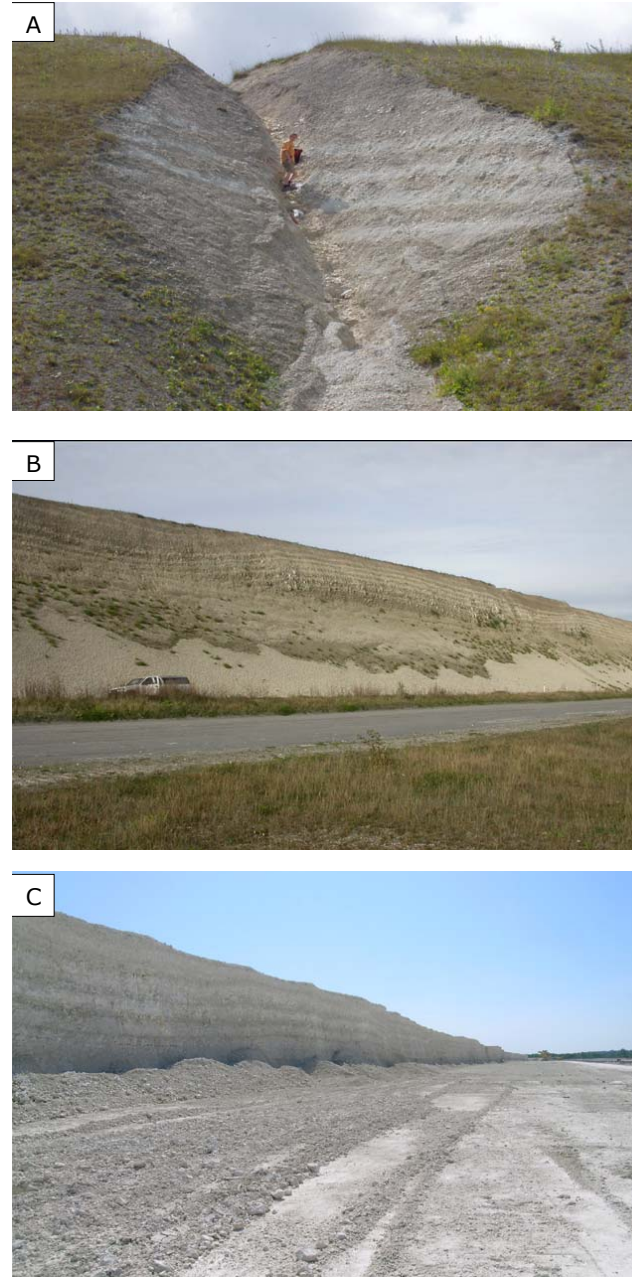


Fig. 2. (A) The type section of the Rørdal Member in the south-western wall of the Rørdal quarry. Position indicated on Figure 1. The exposed section is about 7 m high. (B) The south-western wall of the Rørdal quarry (profile A in Figure 1). Note the gentle glaciotectionic folding of the succession. The wall is about 23 m high. (C) The member is well exposed in the eastern quarry wall which at present (autumn 2009) is being intensely quarried (profile B in Figure 1). The quarry wall is 7 m high.

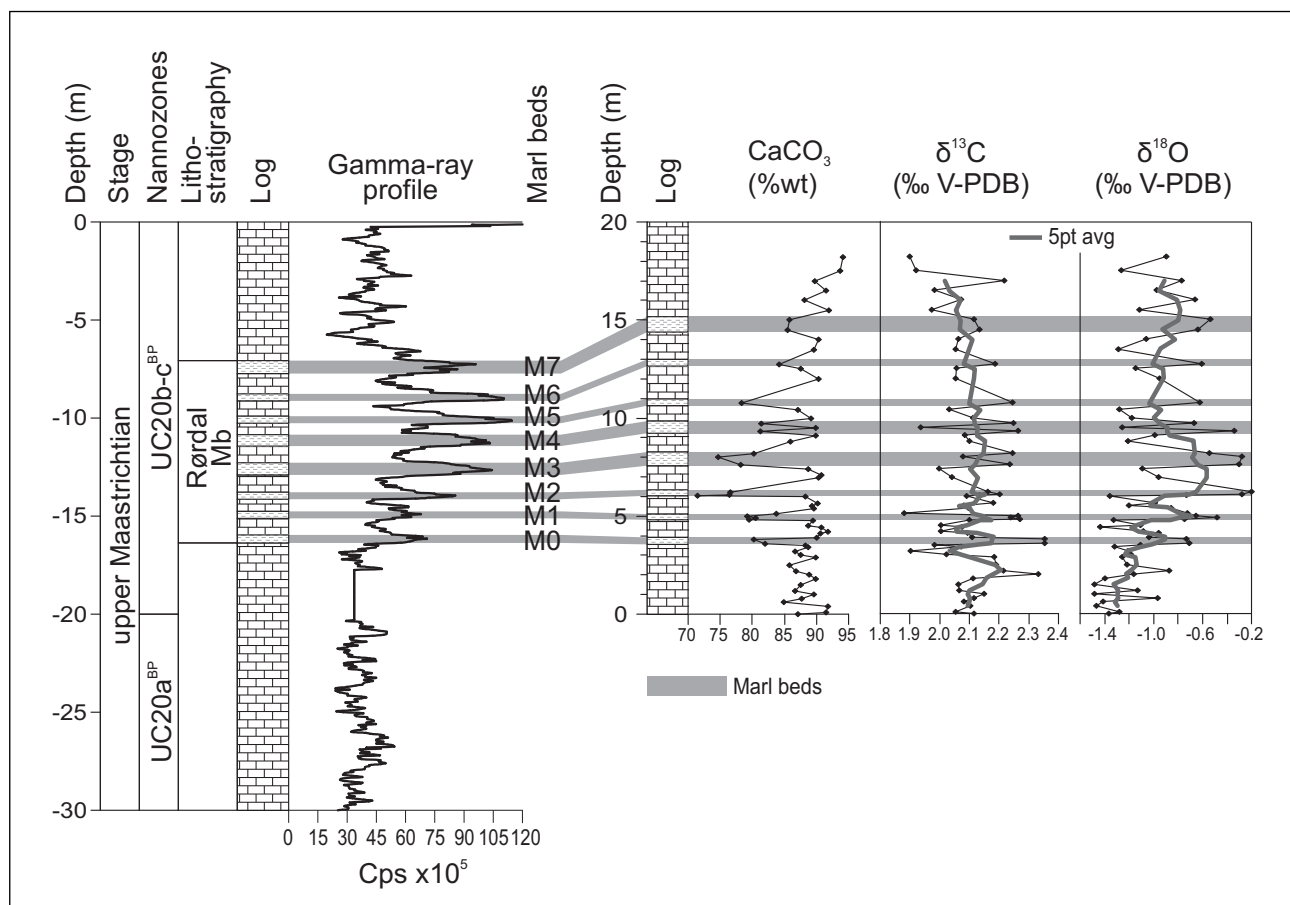


Fig. 3. Stratigraphy, gamma ray log, carbonate content and bulk stable isotopes from the Rørdal quarry section. The Rørdal Member comprises eight marl beds, M0 to M7.

bioturbated chalk (Fig. 4). In the greatly expanded reference section in Karlslunde-1, the eight marl beds are 4–50 cm thick, most being 6–13 cm thick (Fig. 4). The intervening bioturbated chalk beds are mainly 330–480 cm thick, but the uppermost bed is 690 cm thick.

Lithology and fossils

The member comprises a cyclic chalk-marl unit sandwiched between pure white chalks. A total of six marl beds have been identified in the somewhat weathered type section in the Rørdal quarry (Lauridsen & Surlyk 2008). Eight marl beds are visible in the eastern quarry wall and eight beds can be identified in gamma ray logs in a borehole drilled immediately adjacent to the type section (Figs 2, 3, 4). In fresh outcrop and in cores the marl beds are light grey and the intervening chalk is white but in weathered outcrops these colours are reversed and the marl beds are whitish, whereas the chalk beds are light grey (Fig. 2 A, B).

XRD-analyses of the marls indicate that they have a very uniform composition being dominated by smec-

tite and quartz with some illite and minor analcime. Kaolinite is only present in marls from the boreholes in eastern Denmark. The silt fraction is dominated by quartz and dolomite with small amounts of mica, orthoclase and microcline. REE data indicate a very uniform composition of all the marl beds in Stevns-1 and Karlslunde-1 and are characterised by a slight Eu-anomaly (Fig. 5) which is not evident in the marls from the type locality at Rørdal (Ahlborn 2008).

The cyclic occurrence of the marl beds, the clay mineral assemblage, high quartz content, absence of volcanic phenocrysts in the silt fraction, and the lack of a marked negative Eu-anomaly make it unlikely that the marls are weathered volcanic ash-beds, i.e. bentonites. This is further supported by EDX-analyses of individual smectite grains, showing that they are Ca-rich rather than Mg-rich which would be expected if they were authigenic (Ahlborn 2008).

The generally millimetre-sized benthic invertebrate fauna obtained by washing of bulk samples is extremely diverse (Fig. 6). It is dominated by bryozoans estimated to comprise several hundred species, followed by 20 species of echinoderms, 16 species of

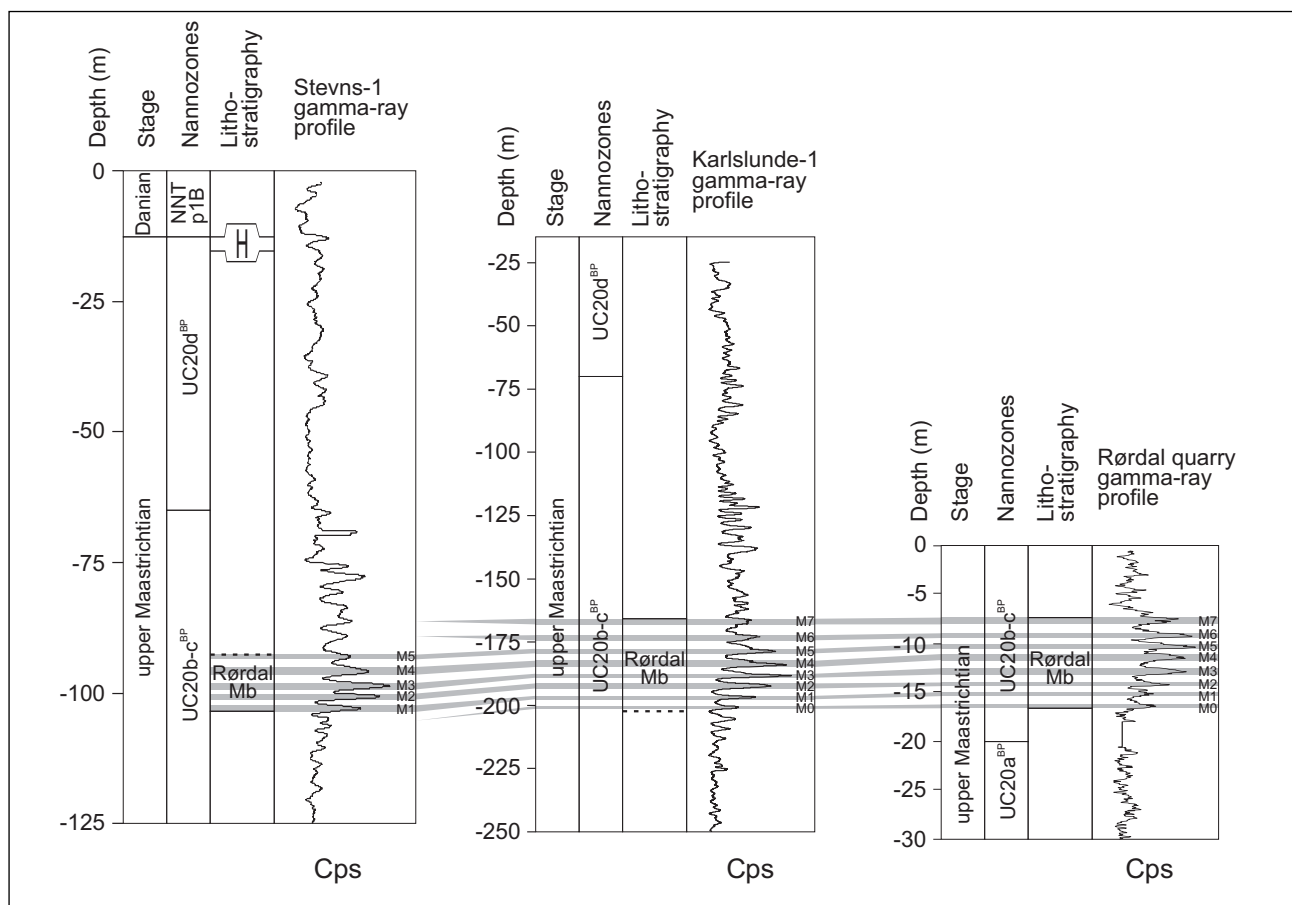


Fig. 4. The Rørdal-1, Stevns-1 and Karlslunde-1 boreholes, showing correlation of gamma ray logs of the Rørdal Member. The two latter boreholes serve as reference localities of the new Rørdal Member. Stratigraphic position of the member is indicated. Based on Stemmerik *et al.* (2006), Schovsbo *et al.* (2008), and Bonnesen *et al.* (2009).

brachiopods, 14 species of bivalves, and 13 species of serpulids (Lauridsen & Surlyk 2008). The member is strongly bioturbated throughout but burrows are more clearly visible and better defined in the marl beds (Fig. 7) (Lauridsen *et al.* in press). The ichnofauna represents the normal spectrum of trace fossils described from the Danish chalk and includes the upper, middle and lower tiers of Ekdale & Bromley (1991).

Stable isotope geochemistry

Oxygen and carbon isotopic composition of bulk carbonates were measured on 63 samples from the type section. The analysis was carried out at the Department of Geography and Geology, University of Copenhagen. The extraction of CO_2 was executed by reaction with anhydrous orthophosphoric acid at 70°C . Analyses were performed with a micromass isoprime spectrometer. The oxygen and carbon isotope values are expressed in per mil (‰) relative to the V-PDB standard reference. The analytical precision is estimated at 0.1‰ for oxygen and 0.05‰ for carbon.

The $\delta^{13}\text{C}$ values range between 1.9 and 2.4‰ and

show an overall linear trend around 2.1‰ throughout the Rørdal Member (Fig. 3). The marl beds tend to have higher $\delta^{13}\text{C}$ values than the chalk beds with a mean difference of 0.3‰ between the two lithologies (Fig. 3).

The $\delta^{18}\text{O}$ values range between -0.2 and -1.5‰ and show a progressive overall increase upwards through the Rørdal Member from mean values of -1.3‰ at the base to values around -0.8‰ at the top (Fig. 3). This trend is interrupted by a positive excursion with values around -0.6‰ between marl beds M2 and M4 (Fig. 3). The marl beds show systematically heavier values than chalk beds with differences that vary between 0.5 and 1‰ between the two lithologies (Fig. 3).

Boundaries

The base of the member is defined by the base of the lowest marl bed in a succession of cyclically interbedded marl and chalk beds. The top of the member is defined by the top of the highest of the marl beds.

Distribution

The member is known from the Rørdal quarry, boreholes south of Aalborg, the Stevns-1, -2 and Karlslunde-1 boreholes south of Copenhagen (this study; Stemmerik *et al.* 2006; Ahlborn 2008; Schovsbo *et al.* 2008). The marl beds have also been identified in water wells in the Aalborg area by the resistivity logs (Jan Jul Christensen, written communication, 2007; Kirsten Skov Nielsen, written communication, 2008) due to the higher conductivity of the clay minerals compared to carbonate.

Bio- and chronostratigraphy

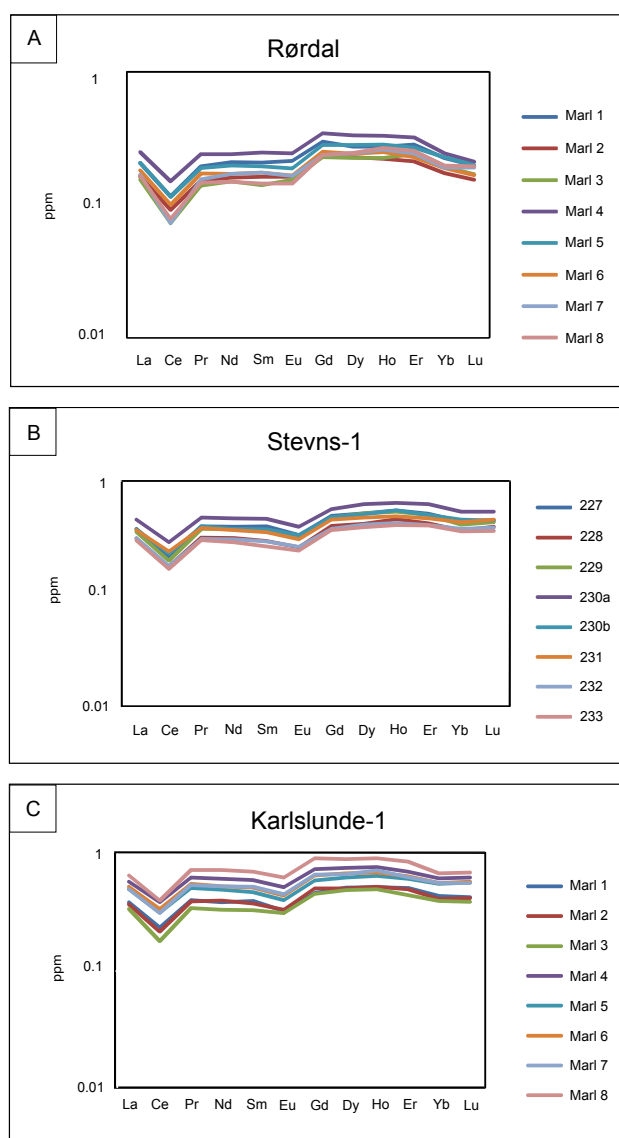


Fig. 5. Plots of REE from the eight marl beds of Rørdal Member from (A) Rørdal Quarry, (B) Stevns-1 and (C) Karlslunde-1. The REE have been normalized to Cody Shale for comparison with bentonite layers in the chalk of northeast England (Wray 1995, 1999). The lack of a defined negative Eu-anomaly in the REE data, combined with a lithology of mixed mineralogy, suggest an allochthonous origin of the marl beds.

The member is placed in the *semiglobularis-humboldtii* brachiopod zone of Surlyk (1970, 1984), and in the UC20b-c^{BP} nannofossil zone (Sheldon, 2008; Thibault 2010), corresponding to the lower upper Maastrichtian (Figs 3, 4).

Provenance

XRD and geochemical analysis of the mineralogy, major elements, trace elements and REE show a uniform composition of all marl beds, suggesting a common source area (Figs 5, 8). Plotting of the trace elements La, Th and Sc against each other reveals high Sc concentrations, suggesting a dominant volcanic contributor in the source area (Fig. 8). Zr/Nb ratios of 6.3–7.3 for all marl beds display a strong alkaline basalt signal while granitic basements would display ratios of 20–40, further strengthening this interpretation (Ahlborn 2008).

An obvious candidate as source area is the alkaline basalt necks and pipes in Skåne in southern Sweden to the east, where marked uplift of horsts took place during Late Cretaceous phases of inversion tectonics (Erlström *et al.* 1997). The stratigraphically younger Kjølbj Gaard Marl has yielded similar results, showing that this area was a source of clay during much of the late Maastrichtian (Ahlborn 2008).

Environmental implications

The differences observed in the oxygen stable isotope values between marl and chalk beds may indicate differences in either temperature or salinity of the sea water during deposition, as well as diagenetic overprinting. Both lithologies are very soft and almost unlithified with only very minor signs of diagenetic influence confirmed by SEM examination of micro-brachiopod valves. The borehole drilled adjacent to the type section was planned as a cored hole but yielded what looked like toothpaste, reflecting the soft nature of the sediments.

The overall progressively upwards increasing trend of the $\delta^{18}\text{O}$ values throughout the Rørdal Member thus seems to indicate an early late Maastrichtian cooling event with a fall in surface sea-water temperature of about 2° (Fig. 3). This interpretation is supported by a significant increase in the abundance of high-latitude calcareous nannofossil taxa in this interval at Rørdal quarry section and in the Stevns-1 borehole (N. Thibault, unpublished data). The variation in $\delta^{18}\text{O}$ between marl and chalk beds may be of primary environmental significance or can be attributed to differ-

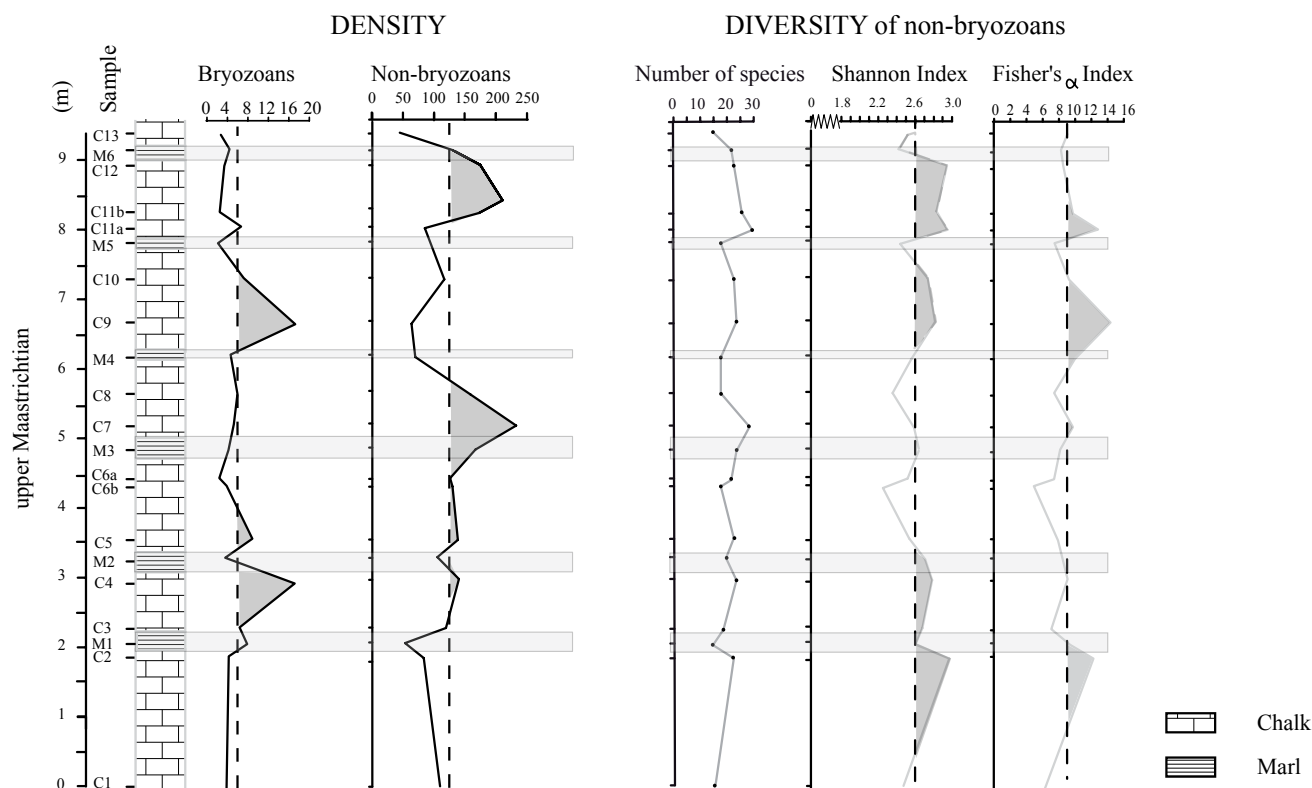


Fig. 6. Faunal density and diversity of the Rørdal Member based on data in Lauridsen & Surlyk (2008). The non-bryozoan group comprises echinoids, brachiopods, bivalves, serpulids, cirripedes, and sponges, which are all identified to species level, whereas the bryozoans are identified as morphotypes only. There is a pronounced difference in species diversity and density of bryozoan morphotypes between chalk and marl samples. Chalk samples are in most cases associated with higher bryozoan and non-bryozoan density and higher non-bryozoan diversity. The density of bryozoans is given g/kg sample due to the relatively high degree of fragmentation caused by sample preparation. The highest density is observed in the chalk between M1 and M2 with more than 14 g/kg. The density of bryozoans in the marl is in most cases below 5 g/kg, but there are slightly more bryozoans in M1. The density of the non-bryozoan macrofauna is also highest in the chalk beds. The density of the well-preserved non-bryozoans is quantified as number of specimens/kg sample. Marl samples are indicated by grey horizontal bars. Dark grey shaded areas indicate density and diversity values above the mean.

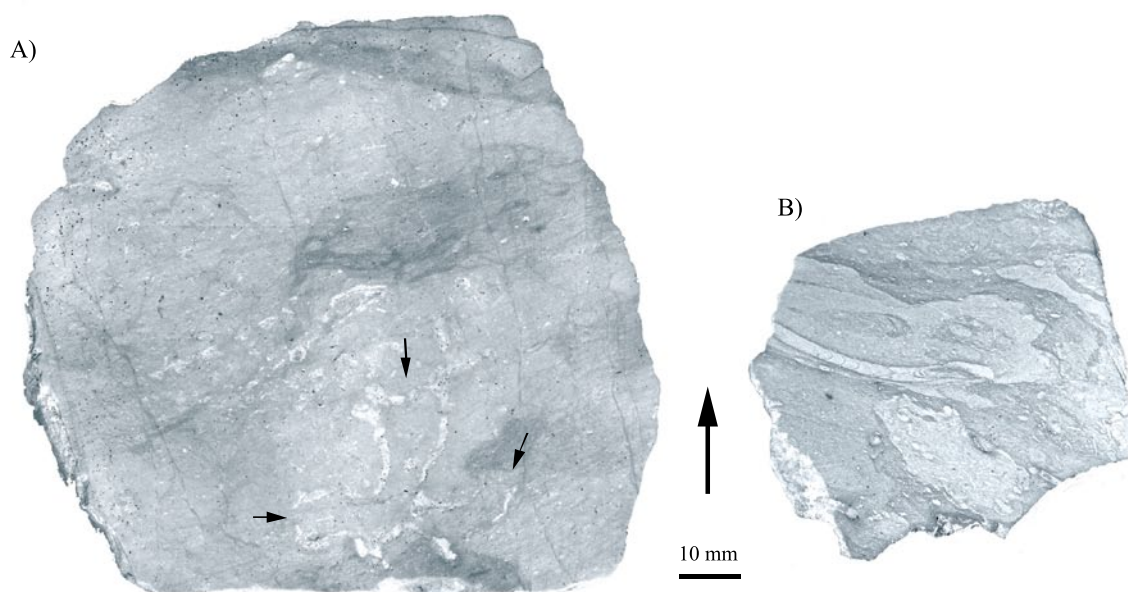


Fig. 7. Bioturbated chalk and marl samples from the Rørdal Member. The arrow indicates stratigraphic way up. (A) Chalk from sample 757, situated 2 m below M1. A possible operculum from a dissolved sponge is marked with small arrows. Note the very low diversity of trace fossils. (B) Marl from sample 722 (M4) shows a very high degree of reburrowing. Several *Thalassinoides* occur and the burrow fills are reburrowed by *Taenidium*, *Zoophycos* and *Chondrites*. *Zoophycos* displays a well-developed reverse backfill.

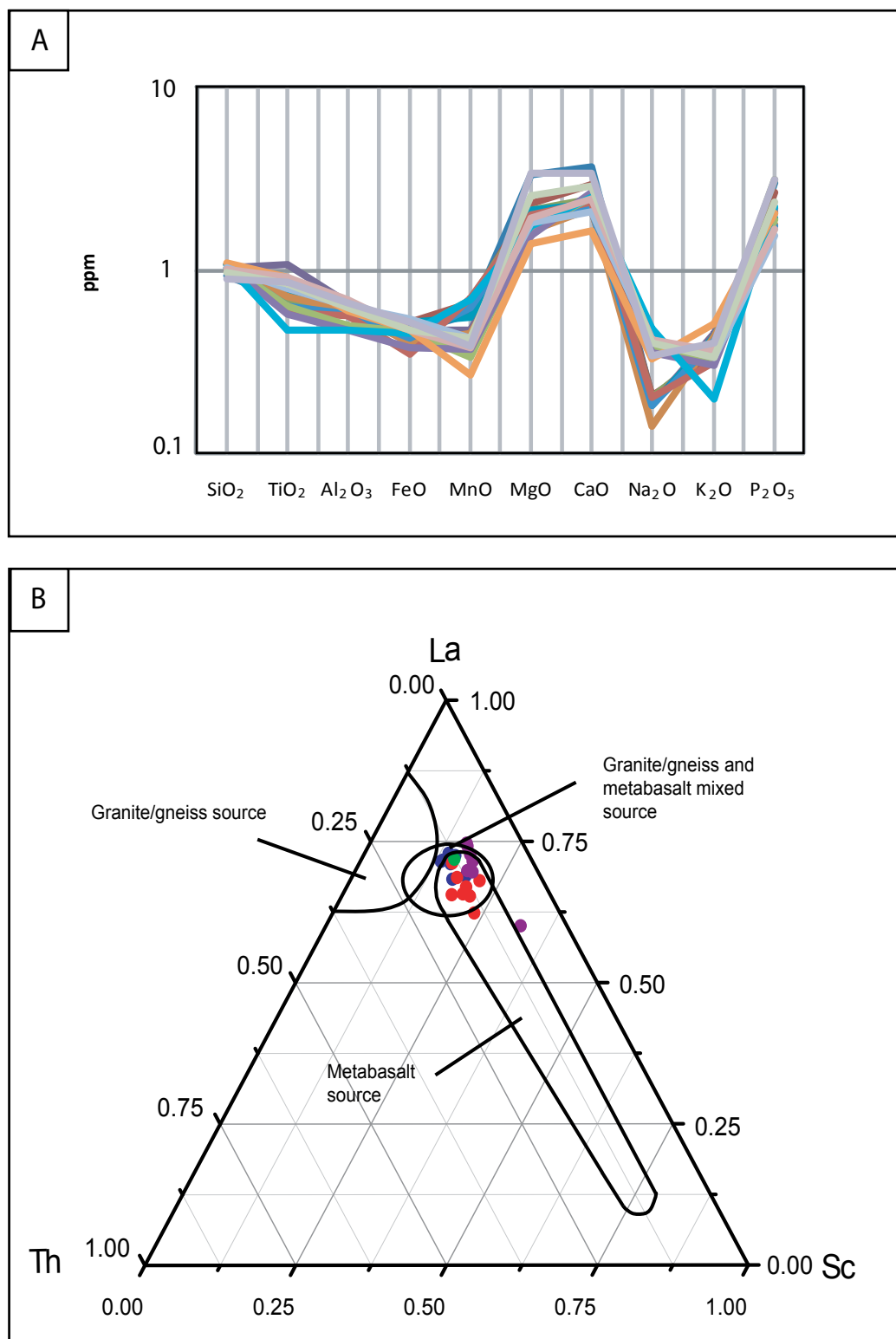


Fig. 8. (A) Plot of major elements from eight marl beds of the Rørdal Member from Stevns-1 and Karlslunde-1, and the Kjølbj Gaard Marl Member from the Tune-1 borehole. The oxides are normalised after the Baltic, Ukrainian and Russian platform following Taylor & McLennan (1985). All marl beds show relative uniform curve patterns which suggest similar source areas. (B) Plot of the ternary relationship between the trace elements La-Th-Sc. All examined marl beds in Stevns-1 (blue), Karlslunde-1 (red), Rørdal (violet) and the Kjølbj Gaard Marl (green) are characterised by compositions that deviate from the geochemical signature of a granite/gneiss basement. The plot illustrates an influence from a Sc-rich source, strongly suggesting a contribution from a volcanic source area. The compositions of the different source areas are from Lee & Lee (2003) and Sinha *et al.* (2008).

ential diagenesis between the two lithologies; ongoing work aims at solving this problem.

The wide distribution of the member in the Danish Basin suggests that the cooling event may be recognised in a larger region and adds to the knowledge of climate changes during the end of the Cretaceous Period.

Acknowledgements

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